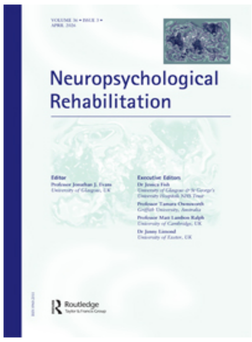

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Relying on the external world after stroke: Individual variability in compensation strategies in working memory use

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ABSTRACT

Capacity tasks are often used to assess working memory after stroke. However, in daily activities, patients may rely on the outside world by (re)inspecting information as needed (i.e., offloading), a strategy that is also advocated in memory rehabilitation. While individuals may use offloading in everyday life to support memory, and choose to memorize only to a low or medium extent, capacity tasks do not allow for nor reflect this. To understand how stroke patients use their working memory when less-than-full-loading is allowed, we recorded eye-movements of patients ($n = 15$) and controls ($n = 38$) as an index of offloading. Both patients and controls avoided working memory loading and relied heavily on offloading. Strategies varied at the individual level, with a subset of patients showing excessive offloading. Interestingly, these patients were also those who showed abnormal capacity scores, but the reverse was not necessarily true. We conclude that low memory capacity is related to, but does not automatically lead to, offloading behaviour. Even when offloading was hampered, maintaining offloading was still more beneficial than switching to a memory-based strategy, supporting the adoption of external strategies in memory rehabilitation. The free-choice paradigm brings us a step closer to estimating working memory use in everyday life.

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Offloading; Memory assessment; Eye movements; Cerebrovascular accident; Copy task

Introduction

Problems in working memory are frequently reported after a cerebrovascular accident (CVA, or stroke; Kimonides et al., 2018; Lugtmeijer et al., 2021). As

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there seems to be a central role for working memory in everyday life activities (Unsworth et al., 2009), working memory deficits can negatively impact patients' level of independence and quality of life (Kimonides et al., 2018; Nys et al., 2006; Tang et al., 2020). Next to focusing on acceptance of these cognitive changes to alleviate the long-term burden (e.g., acceptance and commitment therapy, cognitive behavioural therapy; Rauwenhoff et al., 2023; Verberne et al., 2019), memory rehabilitation aims to support defective (working) memory by optimizing efficient use of the remaining working memory capacity span (e.g., visualization techniques, chunking or grouping, or internal rehearsal; Kaschel et al., 2002; Morrison & Chein, 2011; Norris & Kalm, 2021; Tan & Ward, 2008), but also by using external compensation strategies in order to relief the internal memory load (i.e., *offloading*; Burnett & Richmond, 2023; Elliott & Parente, 2014; Gilbert, 2015; Gilbert et al., 2023; Morrison & Chein, 2011). Memory rehabilitation thus aims to increase independence, and reintegration and participation in society, by targeting effective (working) memory use and increasing self-efficacy in activities of daily life (Cicerone et al., 2005; Saa et al., 2021). Memory rehabilitation is generally found to be effective in improving performance on memory and working memory tasks (Elliott & Parente, 2014).

Strikingly, there is a twofold discrepancy between how we approach working memory function in the clinic and how working memory is engaged in everyday activities. First, in memory rehabilitation, we aim for adequate deployment of working memory in dynamic everyday situations, and advocate using the surroundings (i.e., offloading). In memory assessment, however, patients are instructed to memorize as many items as possible (i.e., full-loading). Patients are forced to use their full memory capacity span (from here on referred to as "capacity") in a distraction-free setting, with little recruitment of other cognitive functions, and no opportunity to exploit the external world. Capacity measures thus do not reflect whether and how patients actually recruit their capacity when they have the choice not to, and thus lack specificity in testing how patients actually *use* their working memory when they are not tied to behavioural instructions. After all, instead of memorizing the entire grocery list, one can simply choose to rely on a written note and look up the required information when in the relevant aisle at the supermarket. Even with a reduced working memory capacity, individuals may not be hindered in carrying out such an activity of daily living. At the same time, individuals with a normal working memory capacity may deliberately choose not to use their maximum capacity and use offloading instead. Second, the premise is that external compensation techniques, such as trained in the clinic, will be spontaneously adopted in more complex environments. Yet, we have little insight into patients' spontaneous strategy deployment, and whether the use of the environment would occur without instruction. If we want to predict whether and how stroke patients will be affected by memory limitations in daily life, we should not only test memory capacity, but acknowledge that working memory is often used in interaction with the environment. The overarching and primary aim of this study is therefore to understand how patients, after stroke, spontaneously use and adapt their working memory in interaction with the environment. We include a neurologically healthy control group and patients in the subacute recovery phase post stroke within an inpatient and outpatient rehabilitation setting; this patient population reflects the population to which memory rehabilitation is generally offered. Although our aim is not to directly compare groups, we do explore regularities across and within groups.

Importantly, we know that there is individual variation in the use of strategies (Böing et al., 2024; Gilbert et al., 2020). Differences in offloading may be driven by (deficient) memory capacity (Böing et al., 2023, 2025; Gilbert et al., 2020; Meyerhoff et al., 2021; Morrison & Richmond, 2020; Risko & Dunn, 2015), but also by effort minimization (Kvitelashvili & Kessler, 2024; Risko & Dunn, 2015) and the desire to be accurate (Burnett & Richmond, 2023). Also, the successful application of memory strategies and monitoring is often linked to intact executive functioning (Bouazzaoui et al., 2010; Bryan et al., 1999; Gathmann et al., 2017; Reuter-Lorenz et al., 2021; Rhodes & Kelley, 2005), suggesting that some individuals may recruit other cognitive domains and can use a strategy more effectively than others. IAs individual differences and preferences are omnipresent, our secondary aim is to specifically address offloading behaviour that may arise from such individual differences. We investigate how measures of memory capacity (as measured by traditional neuropsychological tasks) are related to the individual differences in offloading.

Even though the environment generally remains stable and therefore facilitates external offloading (e.g., by using calendars, whiteboards, planners and cues), information is not always readily available. For example, the grocery list may repeatedly disappear in a pocket filled with keys, gloves and cash, thereby making external information less readily available. The availability of information drastically influences the extent to which people are inclined to use the environment or to memorize; if it takes time or physical effort to retrieve external information, internal memory is relied upon more to circumvent the cost associated with retrieving external information, and vice versa (Ballard et al., 1995; Böing et al., 2023, 2024, 2025; Draschkow et al., 2021; Gray et al., 2006; Hoogerbrugge et al., 2024; Sahakian et al., 2023; Somai et al., 2020). Given that information may be volatile in everyday life, our third aim is to test whether and how stroke patients spontaneously adapt their offloading behaviour (e.g., to a memory-based strategy) when information is not readily available, and how this affects performance. In other words, our third aim is to assess switch costs.

In order to (1) explore offloading behaviour in stroke patients given information availability, (2) address individual differences in offloading, and (3) assess strategy switch costs, we designed a free-choice paradigm in which individuals were allowed to rely on the outside world as a strategy to avoid loading working memory capacity. Participants were instructed to copy a geometric jigsaw puzzle onto an empty grid as quickly and accurately as possible. Participants' eyes were tracked to measure inspection behaviour as an index of reliance on the external world, i.e., offloading. Importantly, we manipulated the availability of external information to test how this affected offloading: the example puzzle was either continuously available for inspection (low-cost condition) or became visible only after a gaze-contingent delay (high-cost condition). Crucially, there was no right or wrong strategy; participants were free to store information at their preferred working memory load, and to choose the frequency with which they inspected the example puzzle. This free-choice reproduction task was designed to elicit behaviour that resembles spontaneous working memory use in everyday tasks where people can rely on the external world. The concept of external strategies covers a wide range of behaviours; external strategies targeted in rehabilitation may focus on slightly different offloading strategies, such as writing things down. However, also when writing is used as form of offloading, one has to (re)inspect the information source to copy the information onto a notebook. The same applies for this (re)inspection behaviour when using written information in the future. Although we do not intent to generalize our findings to *any* other free-choice task, we argue that (re)inspection behaviour is of such a basic nature that it will be exerted in many freedom-of-choice tasks.

Materials and methods

The current study is part of a larger project including multiple patient groups and controls. Part of our control group was also used as a control group in two other studies (Böing et al., 2023, 2025) that addressed different research questions. Note that parts of the Materials and Methods section are nearly identical to those described in the two previous studies. Parts in this section may be paraphrased or copied from the other articles with consent of the authors. We limit the description of the measurements to those relevant for the current research.

Participants

Patients were recruited via the outpatient and inpatient rehabilitation clinic of the Center of Excellence for Rehabilitation Medicine De Hoogstraat. One patient was recruited through the Center for Geriatric Rehabilitation De Parkgraaf. Inclusion criteria were having suffered a stroke, aged between 18 and 85 years old, speaking Dutch, and being able to provide informed consent. Another inclusion criterion was the presence of memory deficits, which was a liberal criterion that could be based either on self-reported memory complaints, objective memory impairment based on neuropsychological assessment, or memory impairment observed by a clinician. The inclusion pace was lower than expected. As patients without profound memory problems could still provide valuable insight in how the symptom (memory capacity) coincides with behaviour (memory use), we decided to broaden our inclusion criteria throughout the study. Exclusion criteria were presence of visuospatial neglect, deficits in visual perception, moderate to severe aphasia, or when motor impairments prevented the use of a computer mouse; assessing these criteria was part of standard care and carried out by clinicians from various disciplines (e.g., (neuro)psychologists, (speech) therapists). The eligibility of patients was based on the judgment of a neuropsychologist and/or a multidisciplinary team within the rehabilitation clinic.

Healthy controls were recruited simultaneously via various public and university platforms (e.g., social media, family members, university intranet, community centres). Controls had to be aged between 18 and 85 years old, speak Dutch, and be able to provide informed consent.

All participants gave written informed consent prior to the start of the experiment. Controls were compensated for their participation with 7EU per hour paid in increments of 30 min, and received compensation for travel costs. Patients were not compensated. The project was approved by the Faculty Ethics Review Board of the Faculty of Social and Behavioural Sciences at Utrecht University (protocol numbers 21-0485, 22-0069 and 22-0284) and the local ethics committee of De Hoogstraat. The protocol was conducted in accordance with the Declaration of Helsinki.

We aimed to include 25 participants in each group. This number was determined by considering previous studies that have tested inspection behaviour. The original trade-off effect on external reliance versus internal storing has been observed in a group of only 7 participants (no mention of effect size; Ballard et al., 1995), which was replicated by Somai et al. (2020) in a group of 12 healthy participants (only unstandardized β coefficients for linear mixed-effect models were mentioned). We expected greater variability in our target group due to the heterogeneity of aetiology and a wider age range, and therefore wanted to increase the sample size. A previous study from our research group in patients with Korsakoff syndrome showed that a sample size of 24 was sufficient to detect differences in eye movement behaviour between patients and healthy controls (detected standardized linear mixed-effects coefficients β were in the range of 0.05–0.38; Böing et al., 2023). We therefore aimed for a similar number.

Measurements

Experimental computer task

Apparatus. We ran the experimental task on a Windows 10 Enterprise computer with an Intel Core i7-4790 CPU and 16GB RAM, and used a 27 inch LCD monitor at a resolution of 2560 × 1440 pixels at 100 Hz for experiment presentation. An EyeLink 1000 (SR Research Ltd., Canada) was placed below the monitor to track the eyes at a sample rate of 1 kHz. Participants sat at ~67.5 cm from the monitor with their heads in a chin-rest. Eye-tracker calibration and validation (following default EyeLink 1000 manufacturing settings) were performed manually with a 9-point grid attempting to achieve a calibration error of less than 2 degrees of visual angle (dva). Specifically, calibration was performed by sequentially presenting dots within the grid. The next dot would only appear after the experimenter confirmed fixation of the current dot.

Copy Task. Identical to our previous studies (Böing et al., 2023, 2025) we used a Copy Task. The task aimed to elicit behaviour that resembles spontaneous working memory use in everyday tasks where people can rely on the external world. The experiment was programmed in Python 3.7 using the PyQt5 library (Riverbank Computing Limited, 2019) for visual presentation and mouse and keyboard interaction. PyGaze (Dalmaijer et al., 2014) was used to interact with the eye tracker.

A model puzzle consisting of 6 items in a 3 × 3 example grid was shown at the left-hand side of the screen (see Figure 1). At the right-hand side of the screen, a 3 × 3 empty grid was presented, with a 2 × 3 resource grid presented below. The resource grid only contained items that were needed to copy the model;

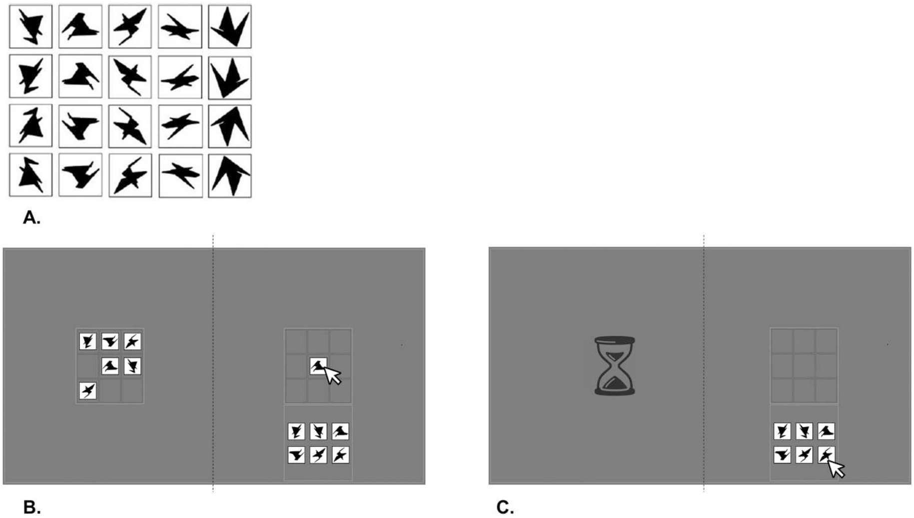

Figure 1. (A) All possible stimuli in the Copy Task. Adopted from Arnoult (1956). An example trial is depicted for the low-cost condition (B) and high-cost condition (C) of the Copy Task. At the left-hand side of the screen, the example grid was either visible or replaced by an hourglass for 2000 ms (i.e., gaze-contingent occlusion). At the right-hand side of the screen, the empty grid to place the items (top) and the resource grid (bottom) are presented. A trial ended after 42 s.

Note: The dotted midline is depicted for illustrative purposes and was not visible in the experiment.

no distractors were present. Items were adopted from Arnoult (Arnoult, 1956; Figure 1(A)) and consisted of black geometrical shapes that could not easily be named to measure reliance on visual working memory instead of verbalization strategies (Somai et al., 2020).

The Copy Task consisted of two experimental conditions. In the baseline or "low-cost" condition, the example grid was visible throughout the trial (Figure 1(B)). In this way, the "cost" to gather information from the outside world was low. In the experimental "high-cost" condition, we raised the cost to inspect information from the external world by introducing a gaze-contingent waiting time: the example appeared after fixating the left side of the screen for a total of 2000 ms. During the waiting time an hourglass was presented (Figure 1(C)). If participants looked back to the right during the waiting interval, the delay-clock would pause, and would restart as soon as the eyes were redirected to the hourglass again, so that gaze-contingent waiting always was 2000 ms, and never more. Once the example grid became visible, it remained on screen until the participant would move their eyes towards the right side of the screen after which it would disappear.

Participants were instructed to rebuild the model puzzle as quickly and accurately as possible by dragging items from the resource grid to the empty grid using a computer mouse. No emphasis was placed on either speed or accuracy. Participants received direct feedback: if an item was placed incorrectly, the item disappeared and the cell turned red for 700 ms, after which subjects could make another attempt. If the item was placed correctly, the cell turned green for 700 ms and the item remained fixed. A trial ended after correct placement of six items, or when the time-limit of 42 s had passed. The time-limit of 42 s was based on the study of Somai et al. (2020) in which high-cost conditions with 200, 1500, and 3000 ms delays were used. The authors observed maximum completion times of 30 s for placing six items in either of the three variations. As we tested older adults and patients with cognitive impairments, we anticipated that participants would need more time. We therefore complemented the maximum observed completion time of Somai et al. (2020) by adding the gaze-contingent delay of 2000 ms for each item that had to be placed in the high-cost condition. In case someone would inspect once per item (which seems plausible from Somai et al., 2020), this would result in an additional 12 s. The choice to impose a time-limit was made because we wanted to have some control over the maximum task administration time, as we were bound to an extensive test protocol with limited testing time. After successful completion of a trial, positive feedback (i.e., a thumbs up symbol) was shown. If subjects failed to correctly place all items within the time-limit, they were informed that they ran out of time. By introducing the time-limit, we encouraged subjects to adopt a time-efficient strategy (Melnik et al., 2018). A drift check (max. 2 degrees visual angle) was performed before each trial, and recalibration was performed when deemed necessary.

First, three practice trials were performed in the low-cost condition to get familiar with the task. Calibration and validation of the eye-tracker were performed after the practice trials. The session started with a low-cost block of 15 trials, followed by a high-cost block of 15 trials, resulting in a total of 30 trials. This blocked design could have led to carry-over effects (Böing et al., 2024; Patrick et al., 2015), but we wanted to make sure that our participants (especially older adults and/or cognitively impaired individuals) understood the basics of the task before being introduced to the more complex gaze-contingent high-cost condition. After each block, participants answered questions on their experience of commitment to and difficulty of the task (not considered in the current analysis). A cycle of the Copy Task took 25 to 45 min, dependent on the calibration time, the participants' work pace, and the number and length of breaks.

We administered one session of the Copy Task for patients, and two for controls, each session consisting of two blocks. For the controls, only data from the first session was described and analysed in the current study.

Eye movement measures. We defined and calculated several outcome measures to describe between-group inspection behaviour on the Copy Task (see Supplementary Materials for elaboration on those), but focus our analyses on the *number of inspections per correct placement* and *inspection time per correct placement*. The *number of inspections per correct placement* refers to the count of only those saccades that cross the midline from right to left, divided by the number of correct placements. This measure captures how often someone needed to inspect the model to correctly place a single item. It reflects inspection behaviour regardless of whether or not someone was able to place all items in time (hence, "per correct placement"), as some trials were not finished in time which would bias the inspection rate. The *inspection time per correct placement* is calculated by dividing the dwell time at the model by the number of correct placements over the course of a trial. This score serves as a measure of how much viewing time (i.e., encoding time) someone needed to correctly place a single item.

Performance measures. We defined and calculated several outcome measures to describe performance on the Copy Task (see Supplementary Materials for the way we calculated variables other than the ones highlighted here). The main outcome used was the linear integrated speed-accuracy score (LISAS; Vandierendonck, 2017, 2021, n.d.). We calculated this LISAS per participant per condition (low-cost, high-cost) as:

$$LISAS = RTij + \ PEij \ x \frac{SRT}{SPE} \tag{1}$$

where *RTij* (reaction time) denotes the trial *i* net copying time (completion time minus hourglass waiting time) divided by the number of correct placements for participant *j*. The reaction time data was log transformed to account for skewness associated with time measures. *PEij* refers to the proportion of errors on trial *i* and equals 1 minus the number of correct placements divided by the total attempts in that trial. *SRT* denotes the participant *j*'s overall net copying time standard deviation, and *SPE* is the participant *j*'s overall *PE* standard deviation. We calculated the standard deviations S_{RT} and S_{PE} per participant over both conditions collapsed (Vandierendonck, 2017, 2021, n.d.). The LISAS was chosen as it combines two outcomes of performance (accuracy and speed) and weighs their importance equally. Lower LISAS reflects better (i.e., more accurate and faster) performance.

Strategy and performance stability. Adapting behaviour from one situation to the other requires flexibility. Switch costs may occur in the transition from one strategy to the other, and participants may differ with regards to how easily they adjust their inspection strategy to the newly imposed conditions. Some may switch effectively and efficiently, whereas others may experience larger switch costs hampering performance. We therefore wanted to explore how spontaneous changes in inspection behaviour may have led to changes in performance. As every individual has a different starting level of performance, it is most informative to test stability/change *within* the individual. To investigate the degree to which each participant adapted their strategy from the low-cost to the high-cost condition, we divided the number of inspections per correct in the high-cost condition by the number of inspections per correct in the low-cost condition and obtained the *change factor number of inspections per correct*. A score of one indicates no change. Scores below one indicate a decrease in the number of inspections per correct, scores above one indicate an increase. The more the value deviates from one, the larger the adaptation in inspecting behaviour from the low-cost condition to the high-cost condition. Note that change factors of 0.5 and 2 indicate a similar magnitude but 0.5 indicates twice as few and 2 indicates twice as many inspections. The same rationale was followed for the performance measure (*change factor LISAS*). For visualization purposes – but not for analysis – the change factor LISAS was centred around zero and flipped.

Neuropsychological tasks

We administered neuropsychological memory tasks that all had a similar task instruction: to memorize and report back as much information as possible. These tasks are all grafted on estimating a maximum capacity span. Standard stimulus set B of the modified Location Learning Task (Kessels et al., 2006, 2014) was used to assess visuospatial immediate recall, and the Rey Auditory Verbal Learning Task (15 items, Dutch version; Bouma et al., 2012; Saan & Deelman, 1986) was administered to assess verbal immediate recall. The Digit Span Forward and Backward from the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV; Wechsler, 2012) were administered to assess short-term auditory memory span and verbal working memory, respectively. A digitized version (2D) of the Corsi Block-Tapping Task was used to assess visuospatial working memory capacity (Brunetti et al., 2014; Claessen et al., 2015; Corsi, 1972; Kessels et al., 2000). Both the Forward and Backward sub-tasks were included. See Supplementary Materials for more details.

Questionnaires

Several questionnaires were administered to characterize groups. Participants were asked whether they experienced memory problems (yes/no). We used the 4-statement Dutch short fatigue questionnaire ("Verkorte Vermoeidheidsvragenlijst") to assess fatigue experienced in the previous two weeks (Alberts et al., 1997; Bleijenberg et al., 2009). The Dutch Hospital Anxiety and Depression Scale was administered to screen for complaints of anxiety (7 items) and depression (7 items) (Spinhoven et al., 1997). The abridged version of the Dutch Metamemory in Adulthood questionnaire was adopted from Ponds and Jolles (1996) to characterize memory self-efficacy. To characterize coping style, the Utrecht Coping List (Gregório et al., 2014; Schreurs et al., 1984) was administered. See Supplementary Materials for more details.

Procedure

Stroke patients

For patients, we divided the test battery into two sessions over separate days (ranging from 1 to 14 days apart). Before the first session, we checked whether patients had already performed some of the neuropsychological tasks as part of rehabilitation care within six months prior to the experiment, but after admittance to the rehabilitation centre. If that was the case, they were exempt from that task; previously reported scores on those tasks were used in order to prevent unnecessary work load and possible practice effects (Bouma et al., 2012; Lezak et al., 2012). Sessions were ended after a maximum of 75 min, or when patients became too tired.

Task administration in the first session comprised (in this order) the following: a memory complaint question (yes/no), short fatigue questionnaire ("Verkorte Vermoeidheidsvragenlijst"), Location Learning Task – direct recall, Copy Task (one cycle of 30 trials), and Location Learning Task – delayed recall. Task administration in the second session comprised (in this order) the following: Rey Auditory-Verbal Learning Task – direct recall, Corsi Block-Tapping Task Forward and Backward, WAIS IV Digit Span Forward and Backward, Rey Auditory-Verbal Learning Task – delayed recall. Patients were asked to fill in three questionnaires (Hospital Anxiety and Depression Scale, Metamemory in Adulthood, and Utrechtse Coping List) in between the sessions. See Supplementary Table S2 for an overview of the test procedure and sessions for stroke patients.

Controls

Participants in the control group received a link to fill out some questionnaires online at home in the period 14 to 1 d(s) before their test session, including the

Verkorte Vermoeidheidsvragenlijst (fatigue), the Hospital Anxiety and Depression Scale and Utrechtse Coping List. These questionnaires were administered to characterize the group. Several other questionnaires were included to collect data for a parallel study (Böing et al., 2025), but are not further described in the current study. The reason is that some of the questionnaires were not suited to administer for patients. For example, the Cognitive Complaints – Participation (CoCo-P) questionnaire focuses on participation upon returning home, whereas many patients were still in patient care. We therefore excluded these for controls as well.

At the university testing facility, the rest of the test protocol was administered in a single visit. The first and second session of the experiment were separated by a break of 10 to 20 min, and the total test duration was a maximum of 3 h. Task administration in the first session comprised (in this order): Location Learning Task–direct recall, Copy Task (first cycle of 30 trials), Location Learning Task–delayed recall, WAIS IV Digit Span Forward and Backward, and if time allowed: a Fixation and Free viewing task (not taken into account in the current study). Task administration in the second session comprised (in this order): Rey Auditory-Verbal Learning Task–direct recall, Copy Task (second cycle of 30 trials; not taken into account in the current analysis, see Pre-processing), Rey Auditory-Verbal Learning Task–delayed recall, Corsi Block-Tapping Task Forward and Backward, and if time allowed: Change Detection Task (not taken into account in the current study).

At the end of the test protocol, the Metamemory In Adulthood questionnaire was administered. This was the case only for a subset of participants ($n = 15$) as the questionnaire was added later to the test protocol (as part of Böing et al., 2025). This questionnaire was added to get an extra measure on beliefs about one's memory function. See Supplementary Table S2 for a schematic overview of the test procedure.

Pre-processing

Inspection behaviour

Saccades, fixations, and timestamps were extracted using the EyeLink 1000 parser (default EyeLink saccade detection algorithm, SR Research Ltd., Canada). Data pre-processing was implemented using Python 3.10. Every first trial in each block was removed from analysis (see Results, Data Loss): this trial served to check whether the instructions had been retained (additional instructions were given when needed) and to habituate the participant to the new situation (e.g., from low-cost to high-cost). Eye-movement and performance variables were calculated as described in Measurements and Supplementary Materials. Note that patients performed one cycle of the Copy Task while controls performed two. To ensure comparability between groups, we only used data of the first cycle for the control participants. Data analyses were conducted using R 4.1.2 (R Core Team, 2017).

Individual strategy categorization

Participants were categorized based on the number of inspections per correct placement. For each individual, this outcome measure was aggregated by the mean over trials per condition (low-cost, high-cost). Those who made on average more than one inspection per correctly placed item were categorized as "low-loaders," i.e., those who relied relatively heavily on the external world. Participants who correctly remembered one item or more per inspection were categorized as "medium-loaders," i.e., those who successfully relied more on internal loading. Those who correctly placed three or more items per inspection could be further categorized as "high-loaders," i.e., those who loaded up to the limits of their capacity. These category cut-offs were partly based upon the finding that people have an estimated working memory capacity of four items (Cowan, 2001), and partly based upon task constraints. The Copy Task did not have a high enough resolution to dissociate between people loading three, four, or five items, as in all of these instances, participants would need an additional inspection for the remaining items, yielding two inspections for trial completion. It is important to keep in mind that people are claimed to have an estimated working memory capacity of four items (Cowan, 2001), but for more complex shapes such as polygons, this maximum capacity seems to be decreased (Alvarez & Cavanagh, 2004; Luria et al., 2010; Luria & Vogel, 2011). Determining whether or not individuals were loading their full working memory capacity is not possible due to the lack of resolution, but the high-loading categorization still captures the higher end of capacity use. The current categorization system was adopted from Böing et al. (2024) and slightly adapted to the current task characteristics.

Clinical classification

We used a classification to identify patients with memory impairments, defined as performing outside the normal range on neuropsychological memory capacity task outcomes. We defined the levels of performance in memory capacity based on a subset of the tasks administered: Location Learning Task – displacement errors, Rey Auditory-Verbal Learning Task – immediate recall score, Digit Span Forward, Digit Span Backward, Corsi Block-Tapping Task Forward, and Corsi Block-Tapping Task Backward. Each individual's scores were compared to scores of their reference group (in terms of age and education) as is common in clinical assessment. The level of performance was defined as either within or outside the normal range. An abnormal score could be any of the following: (1) a score below the 2nd percentile on two or more subtasks (e.g., impaired performance), (2) a score below the 2nd percentile on one subtask and/or a score between the 2nd and 9th percentile on two or more subtasks (e.g., below average performance). A normative score was anything outside these definitions (American Psychiatric Association, 2013; Nederlands Instituut van Psychologen, 2025).

The delayed recall scores of the Location Learning Task and Rey Auditory-Verbal Learning Task were not taken into account, as we could not assure that the delay period was equally long for all the participants and the interference tasks differed between controls and patients. These factors could differentially interfere with memory performance, making delayed recall scores unsuitable for clinical classification. We report the delayed recall scores in the Results section for completeness, but did not use them for clinical interpretation.

Changes in inspection frequency and changes in performance: Switch costs

We calculated the change in inspection behaviour as:

$$Log\ change\ in\ inspection\ frequency = \log \frac{number\ of\ \ inspections\ per\ correct_{high\ cost}}{number\ of\ \ inspections\ per\ correct_{low\ cost}}$$

We calculated the change in *LISAS performance* as:

$$Log\ change\ in\ LISAS = -\left(\log \frac{LISAS\ in\ high\ cost}{LISAS\ in\ low\ cost}\right)$$

That we flipped the values of LISAS so that negative values indicate a decrease in performance and positive values indicate an improvement. Log-transformation of the values alleviates skewness of data, and creates symmetry in positive and negative outcomes. Yet, it does not guarantee a normal distribution. Therefore, and to account for small sample sizes, we used bootstrapping (see Methods – Data analyses) with 10.000 resamples with resampling size of 30 from the pool of controls.

Data analyses

Group characteristics

Demographic similarity in groups was assessed post-hoc. Scores on neuropsychological tasks and questionnaires were reported to characterize groups. Group differences were tested using parametric Welch’s t-tests, non-parametric Mann–Whitney-Wilcoxon tests, chi-squared tests, or proportion z-tests, depending on assumption checks.

Strategy conceptualization check

We ran a non-parametric Kendall Rank correlation between the *number of inspections per trial* and *inspection time per inspection* (note: not the “per correct” placement scores) in the low-cost condition (both groups collapsed). We expected that a higher number of inspections would relate to shorter inspection times per inspection, and vice versa. Fewer inspections with longer inspection times would reflect a tendency towards memorization, as more time inspecting would indicate an attempt to encode more items at once. Correlation coefficients were reported as tau (τ) and effect sizes as z.

Group inspection behaviour

Although our aim was not to directly compare groups, we tested the influence of group and information availability on inspection behaviour and performance for completeness and to provide data for a potential future meta-analysis on Copy Task behaviour. To this end, all trials were fed to a linear mixed-effect model (LMM; Singmann & Kellen, 2019) by using the lmer function in R (lme4 package; Bates et al., 2014) with factors group (stroke, control), condition (low-cost, high-cost), and the interaction of group and condition, and random slope and intercept for individuals. We elaborate on this analysis in the Supplementary Materials.

Individual strategy categorization, clinical classification and single case statistics

The main goal of this study was to describe individual differences in strategies. We therefore classified participants as "low-loader," "medium-loader," or "high-loader," based on the *number of inspections per correct placement* (see Pre-processing). An external strategy translates to a high mean number of inspections per correct placement (low-loading), whereas an internal memorization strategy translates to a low mean number of inspections per correct placement (i.e., longer encoding per iteration; medium- and high-loading). We provided the percentages of participants falling within each category (low-loader, medium-loader, high-loader) for each condition (low-cost, high-cost) for both groups (CVA, controls), and noted the number of inspections per correctly placed item for low-loaders, medium-loaders and high-loaders. Note that we are *not* using our categorization for statistical analyses, but solely for descriptive purposes.

Single case Bayesian Deficit Testing, with the covariate age, was used to further assess whether inspection behaviour of each individual patient statistically deviated from that of healthy controls. We performed a one-tailed Bayesian Deficit Test with $\alpha = 0.05$ and 10,000 iterations on *the number of inspections per correct placement* (with the covariate age) using the singcar package in R (Rittmo & McIntosh, 2021). Bayesian Deficit Testing allows to assess single cases against a norm group of healthy controls: it takes a single observation and compares it to a distribution estimated by a control sample, using Bayesian methodology (Rittmo & McIntosh, 2020, 2021, 2023).

Strategy shifting and performance stability: Switch costs

We assessed whether changes in inspection behaviour across conditions (from low-cost to high-cost) were related to changes in performance (from low-cost to high-cost) – in other words, we assessed switch costs. We used the log-transformed change in inspection frequency and the log-transformed change in LISAS performance as described in pre-processing to counteract non-normality. We used parametric Pearson correlations to test the correlation coefficients for the group as a whole and for the groups separately. To assess whether the correlation coefficients of controls and patients were significantly different and/or were driven by sample size differences, we conducted bootstrapping with 10.000 resamples (with set seed for reproduction) using a resampling size of 15 (out of 38 controls) without replacement to match the group size of patients. We report the bootstrapped mean estimate r for the subsampled control correlation, 95% confidence intervals, and *p*- and *z*-values, and contrast the observed patient correlation. $p < .05$ is considered significant.

Code and software

Experiment code, raw and pre-processed eye movement data, raw scores on neuropsychological assessment, and analysis scripts are publicly available and can be found at Open Science Framework via: https://osf.io/95zx7.

Results

Group characteristics

Descriptives

We approached 28 patients of whom 19 agreed to participate. Of these, three were excluded due to prematurely ending the test session because the participant was not able to complete the Copy Task or because we could not track their eyes due to a failure of the eye-tracker or a medical condition. Another participant completed the protocol but was excluded a posteriori as it appeared that there was no stroke history but another medical condition. Eventually, we were able to obtain datasets of 15 patients (see Supplementary Figure S3 for a patient flow chart; see Table 1 for lesion information, demographic characteristics and test scores). The sample of stroke patients was smaller than anticipated due to stagnated inclusion in the aftermath of COVID-19 and under-occupation of beds.

Forty-eight healthy participants were recruited as control group. Four cancelled their appointment due to personal reasons and did not wish to reschedule, four were not tested on the Copy Task due to technical problems, one completed the protocol but appeared to not meet our inclusion criteria, and for one we were unable to track the eyes. Eventually, we obtained datasets of 38 individuals (see Table 1 for demographic characteristics and see Supplementary Figure S3 for a control flow chart). Note that part of the healthy control data was reported in a previous study (Böing et al., 2025).

Group characteristics, scores on neuropsychological assessment and questionnaires, and statistical comparisons between groups are displayed in Table 1. The level of education was characterized according to the classification of Verhage (1964, 1965), that is commonly used in Dutch clinical care, and classifies

Table 1. Demographic characteristics, scores on memory capacity tasks, and questionnaires, split per group (i.e., stroke patients or healthy controls), medians (IQR) or frequencies (%) are depicted.

	CVA patients			Healthy controls			Test Statistic[a]
	n	*n* (%)/ Mdn (IQR)	Range	*n*	*n* (%)/ Mdn (IQR)	Range	
Demographics							
Age, years	15	61 (8.5)	49–84	38	60	40–81	$t = -0.1$, $p = .91$, $d = -0.03$
Sex, % male	15	10 (66.7%)		38	15 (39.5%)		$\chi^2 = 2.19$, $p = .139$, $d = -0.42$
Level of education[b]	15	6 (1.5)	3–7	38	6 (1.75)	4–7	$U = 318$, $p = .506$, $r = 0.12$
% low (<10 years)		4 (26.7%)			5 (13.2%)		
% medium (10–11 years)		3 (20%)			12 (31.6%)		
% high (>15 years)		8 (53.3%)			21 (55.3%)		
Lesion information							
Time post-stroke onset, days	15	74 (46.5)	36–137				
Stroke history, % first	15	86.7%					
Stroke type	15						
% ischemic		11 (73.3%)					
% intracerebral hemorrhage		3 (320%)					
% subarachnoid hemorrhage		1 (6.7%)					
Lesion side,	14[c]						
% left		11 (78.6%)					
% right		2 (14.3%)					
% bilateral		1 (7.1%)					
MoCA (0–30)	15	24 (4)	18–30				
SAN (Aphasia Index; 1–7)	15	6 (2)	4–7				
Barthel Index (0–20)	15	13 (7.5)	5–19				
Motricity Index Arm (0–99)[d]	15	76 (80)	0–100				
Motricity Index leg (0–99)[d]	15	83 (39)	0–100				
Mood, fatigue and coping questionnaires							
Do you experience memory problems? %yes		6 (40%)		38	9 (23.7%)		$\chi^2 = 0.72$, $p = .396$, $d = 0.24$
Fatigue, % severe fatigue	15	6 (40%)		38	6 (15.8%)		$\chi^2 = 2.35$, $p = .123$, $d = -0.43$
Anxiety & Depression Scale (HADS)							
Anxiety (HADS)	15			38			
Not present (score 0–7)		15 (100%)			31 (81.6%)		
Potential (score 8–10)		0 (0%)			7 (18.4%)		
Likely (score ≥11)		0 (0%)			0 (0%)		

Depression (HADS)							
Not present (score 0–7)		11 (73.3%)			36 (94.7%)		
Potential (score 8–10)		4 (26.7%)			2 (5.3%)		
Likely (score ≥11)		0 (0%)			0 (0%)		
Total score		7 (6.5)	0–16		5 (7.75)	0–19	$U = 248$, $p = .470$, $r = -0.13$
Coping style (UCL)	14			38			
Active		19.5 (5.74)	8–24		19 (7.75)	7–28	$t = 0.73$, $p = 0.47$, $d = 0.21$
Palliative		16 (3)	8–23		15.5 (4.75)	8–22	$t = -0.47$, $p = 0.64$, $d = -0.16$
Avoidant		15.5 (6)	9–21		15 (4)	8–22	$t = -0.37$, $p = .71$, $d = -0.12$
Social support		12 (1.75)	6–15		12 (4)	6–24	$t = 1.16$, $p = .25$, $d = 0.28$
Passive		9.5 (3)	8–14		11 (5.75)	7–18	$U = 285$, $p = .700$, $r = 0.07$
Emotional expression		5 (1.75)	3–8		6 (2)	3–9	$t = 2.16$, **$p = .041$***, $d = 0.64$
Comforting		13 (4)	6–15		12 (3)	5–19	$t = -0.99$, $p = .33$, $d = -0.31$
Neuropsychological task scores							
Location learning task	15			38			
Total displacement score^{e}		29 (40.5)	6–101		27.5 (26)	0–75	$t = -0.68$, $p = .5$, $d = -0.24$
Learning index (0–1)		0.47 (0.28)	0.136–0.95		0.52 (0.42)	0.101–1	$t = 0.53$, $p = .6$, $d = 0.15$
Delayed recall: Placement errors		1 (7)	0–17	37	1 (4)	0–19	$U = 252$, $p = .587$, $r = -0.09$
Rey auditory–verbal learning task	14			37			
Immediate recall: Total correct (0–75)^{e}		34 (20.2)	18–54		42 (18)	30–67	$t = 2.39$, **$p = .026$***, $d = 0.80$
Delayed recall: Total correct (0–15)		6 (4.5)	0–14		8 (6)	3–14	$U = 357$, **$p = .039$***, $r = 0.38$
Digit span (WAIS-III/IV)	13			38			
Forward span (2–9)^{e}		5 (1)	4–7		6 (2)	4–9	$U = 318$, $p = .111$, $r = 0.29$
Backward span (2–8)^{e}		4 (0)	3–5		5 (2)	2–8	$U = 357$, **$p = .014$***, $r = 0.45$
Corsi block-tapping task	15						
Forward span (2–9)^{e}		5 (0.5)	4–7	38	5 (1)	3–8	$U = 330$, $p = .345$, $r = 0.16$
Backward span (2–8)^{e}		5 (2)	4–8	37	6 (1)	2–7	$U = 318$, $p = .393$, $r = 0.15$
Impairment within memory domain^{f}							
% impaired		0 (0%)			2 (5.3%)		
% below average		6 (40%)			5 (13.2%)		
% within normal range		9 (60%)			31 (81.5%)		
Memory capacity compound, z	15	−0.17 (0.76)	−1.42–1.36	38	0.14 (0.91)	−1.35–1.43	$t = 1.80$, $p = .08$, $d = 0.55$
Metamemory In Adulthood	14			15			
Scale Achievement (+ = high achievement)		3.5 (0.24)	2.71–4.0		3.71 (0.57)	2.43–4.5	$t = 0.70$, $p = .49$, $d = 0.25$
Scale Anxiety (+ = high knowledge; lower is better)^{g,h}		2.36 (0.583)	1.58–3.76		2.67 (1.04)	1.25–4.00	$t = -0.77$, $p = .45$, $d = -0.27$
Scale Capacity (+ = high capacity)^{h}		3.75 (2.86)	2.25–3.75		3.25 (0.58)	2.58–4.50	$t = 1.88$, $p = .07$, $d = -0.67$
Scale Change (+ = stability)^{h}		3.55 (0.6)	1.60–4.40		3.2 (0.65)	2.11–4.30	$t = -0.66$, $p = .51$, $d = -0.24$

(*Continued*)

Table 1. Continued.

	CVA patients			Healthy controls			Test Statistic[a]
	n	*n* (%)/ Mdn (IQR)	Range	*n*	*n* (%)/ Mdn (IQR)	Range	
Scale Locus (+ = internal locus)		3.22 (0.29)	1.71–3.86		3.14 (0.57)	2.00–4.14	$U = 82.5$, $p = .333$, $r = -0.21$
Scale Task (+ = high knowledge)		3.55 (0.475)	2.80–4.20		3.5 (0.45)	2.70–4.5	$t = -0.26$, $p = .80$, $d = -0.09$
Scale Strategies Total (+ = high use)		3.25 (0.814)	1.50–4.75		3.44 (0.722)	2.31–5.00	$t = 0.64$, $p = .53$, $d = 0.23$
Scale internal strategies		3 (0.688)	1.50–4.88		3.5 (0.688)	2.38–5.00	$t = 1.23$, $p = .23$, $d = 0.45$
Scale external strategies		3.56 (0.782)	1.50–4.75		3.5 (0.558)	2.25–5.00	$t = 0.06$, $p = .96$, $d = 0.02$
Sum score		3.34 (0.557)	2.58–4.19		3.27 (0.57)	2.26–4.42	$t = 0.03$, $p = .97$, $d = 0.01$
Memory Self-Efficacy[g] (+ = higher efficacy)							

Note: CVA = cerebrovascular accident (stroke), Mdn = median, IQR = interquartile range, range (min.–max.), MoCA = Montreal Cognitive Assessment; SAN = Stichting Afasie Nederland. Sample size may differ per outcome variable.

[a] Parametric and nonparametric test statistics indicating group differences and effect sizes: chi-squared, *p*-value, and d for binomial variables, Welch *t*-test, *p*-value and Cohen's d (Hedges' corrected) or Mann–Whitney–Wilcoxon U, *p*-value, and rank-biserial correlation r.

[b] The level of education is characterized according to the classification of (Verhage, 1964, 1965), that is commonly used in Dutch clinical care, and classifies the level of education (ranging from 1 to 7) based on the number of education years.

[c] One unknown.

[d] Motricity Index maximum score is 99. However, if both arm and leg score 99/99, one point may be added, so a score of 100 is possible and indicates intact arm and leg function.

[e] Capacity scores used in memory capacity compound z-score; Location Learning Task displacement errors are reversed so that higher scores indicate better performance on all capacity tasks.

[f] Impaired: a score <2nd percentile on ≥ 2 sub tasks[e]; Below average: a score <2nd percentile on 1 sub task[e] and/or a score between 2nd – 9th percentile on ≥ 2 sub tasks[e]; Within normal range: does not fit criteria for impairment or below average.

[g] Anxiety scale is reversed in calculation of the Memory Self-Efficacy sum score, so that higher scores indicate better subjective memory experience.

[h] Scores used in calculation of memory self-efficacy; higher scores indicate better subjective memory experience.

$^{*}p \leq 0.05$.

$^{**}p \leq 0.005$.

$^{***}p \leq 0.001$.

the level of education (ranging from 1 to 7) based on the number of education years. All individuals were without known visual field defects and had normal or corrected-to-normal visual acuity. If patients already completed tasks from our protocol as part of standard care, they were exempt from this task. We report the scores obtained from their medical file. Three patients already completed the Location Learning Task. Eleven patients were exempt from the Rey Auditory-Verbal Learning Task and the Digit Span Task. The average period between the assessments that were part of standard care and our experiment was 3.65 weeks.

Data loss

Datasets were obtained for 15 participants in the stroke population. Across these 15 participants, 450 trials were planned to be collected (15 trials x 2 conditions x 15 participants). All first trials of each block were removed to assure task comprehension (30 trials). Any reason that could possibly interfere with performance (excessive movement of the participant, forgetting the task instructions, problems controlling the mouse) was logged, and the corresponding trials (19 trials) were removed from further analysis. No trials were lost due to exceeding the drift check. During data pre-processing, we checked for deviant trials that yielded invalid data due to corrupted eye-tracking logging (e.g., zero fixations per second, dwell times of zero, or missing data), of which most coincided with the logged trials. One additional trial was discarded due to a logged dwell time that exceeded the duration of the trial, which should be attributed to an eye-tracking failure. Finally, 401 trials were left for analysis.

Across 38 participants in the control group, 1140 trials were planned to be collected (15 trials x 2 conditions x 38 participants). Again, the first trials of each block were removed (76 trials). Trials that were invalid due to signal loss, excessive movement of the participant, forgetting the task instructions, or problems controlling the mouse were removed (9 trials). Despite the implementation of a drift check, some trials were started with a drift check above the 2 degrees visual angle threshold. When exceeding 5 degrees visual angle, trials were excluded. In total, 9 trials needed to be excluded because of exceeding the drift check threshold. In the control group, 1046 trials were left for analysis.

Strategy conceptualization check

There was a strong negative correlation between the number of model inspections and dwell time per inspection per trial across *all* trials ($\tau = -0.605$, $p < .001$, $z = -33.27$), indicating that fewer model inspections were related to longer inspection durations. This finding substantiates our conceptualization that the number of inspections can be used as an index of memorization.

Group inspection behaviour

Our primary focus was on individual differences within the groups, but we compared groups for completeness. The smaller sample size for the stroke population could have comprised power for this group comparison. However, effects of condition on inspection behaviour are generally large: a recent meta-analysis (Qing et al., 2025) showed that especially the number of inspections optimizes both sensitivity and specificity, and was associated with large effect sizes. With our total sample of 53 participants and repeated-measures design, we were confident that we had sufficient data for our analyses of inspection behaviour. We used linear-mixed effect models that weighted the number of observations (Schielzeth et al., 2020; Singmann & Kellen, 2019, see Methods).

Group scores for inspection behaviour and performance across conditions (low-cost and high-cost) were calculated, reported and analysed in the Supplementary Materials, Table S4 and Figure S5. Patients used more and longer inspections than controls to place one item correctly, and performed worse than controls.

Individual strategies: Strategy categorization, clinical classification and single case statistics

To answer our main question, namely how *individual* patients use their memory, we descriptively report and visualize the distribution of used strategies across individuals, and look into the clinical meaningfulness of such a categorization. Figure 2 shows inspection behaviour across the low-cost and high-cost condition for

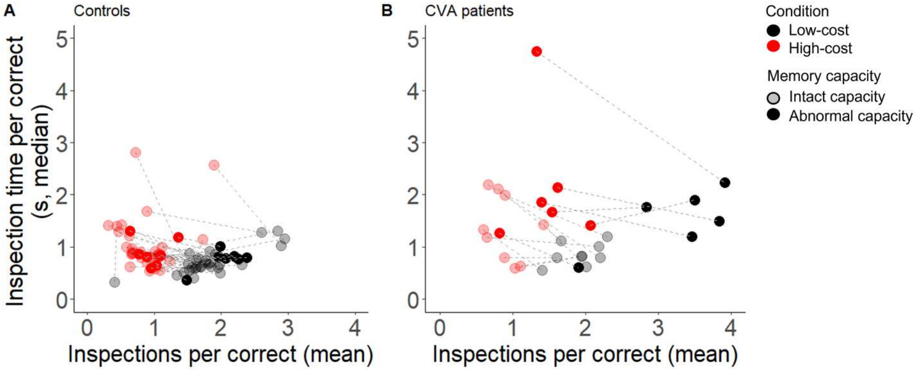

Figure 2. Offloading behaviour, presented as median inspection time per correct placement (e.g., encoding time per item) and the average number of inspections per correct placement for the two groups: (A) healthy controls, (B) CVA (stroke) patients. Data points represent data of the individual aggregated over trials in the low-cost condition (black) and high-cost condition (red). Dashed lines connect the data that belong to the same individual, and indicate the change in inspection frequency for an individual from low-cost to high-cost (i.e., change factor for inspections). Saturated dots indicate individuals that showed below average or impaired (thus, abnormal) memory performance on traditional neuropsychological memory capacity assessment.

Table 2. Mean number of inspections per correctly placed item per group (stroke (CVA) patients, controls), per condition (low-cost, high-cost) and per strategy category (low-loader, medium-loader, high-loader).

		Group					
		CVA patients ($n = 15$)			Controls ($n = 38$)		
Condition	Strategy category	*n* (%)	Mean (SD)	Range	*n* (%)	Mean (SD)	Range
Low-cost	Low-loader	15 (100%)	2.45 (0.84)	1.41–3.91	37 (97.4%)	1.92 (0.41)	1.33–2.95
	Medium-loader	0			1 (2.6%)	0.40 (n.a.)	n.a.
	High-loader	0			0		
High-cost	Low-loader	8 (53.3%)	1.44 (0.32)	1.03–2.07	15 (39.5%)	1.19 (0.27.)	1.01–1.89
	Medium-loader	7 (46.7%)	0.75 (0.12)	0.6–0.89	22 (57.9%)	0.72 (0.15)	0.44–0.95
	High-loader	0			1 (2.6%)	0.31 (n.a.)	n.a.

Note: We provide the number of individuals (%) per category based upon the number of inspections per correct, and the mean, standard deviation, and range of the number of inspections per correct.

individuals, separately for healthy controls and patients. We marked the individuals that classified as having abnormal memory function as measured with neuropsychological capacity tasks (i.e., impaired or below average performance within the memory domain, see Methods). Table 2 displays the proportions of low-loaders, medium-loaders, and high-loaders across groups and conditions.

In the low-cost condition, almost everyone heavily relied on the external world: 100% of patients and 97.4% of controls were categorized as low-loader. When imposing high-costs, the percentages dropped: 53.3% of patients and 39.5% of controls adhered to low-loading, whereas 46.7% of patients and 57.9% of controls started medium-loading. None of the patients and only one control was classified as high-loader. Looking at individual data points, there was quite some variability within these categories. Some low-loaders inspected twice per correct item, but there were also individuals that used on average three to four inspections to place one item correctly.

Interestingly, in both groups we identified individuals that had abnormal memory capacity, indicating a deficit in memory *capacity* for these individuals. In the CVA group, the individuals with a deficit in memory load seemed to present as a cluster in their inspection behaviour (Figure 2(B), saturated dots), showing a relatively high number of inspections per correct placement and a long inspection duration. However, in the healthy control group, those with a deficit in memory load did not show such distinct inspection behaviour (Figure 2(A), saturated dots). To further assess whether inspection behaviour of the subgroup of stroke patients with memory impairment statistically deviated from normal, we performed a one-tailed Bayesian Deficit Test on the number of inspections per correct placement in the low-cost condition for each patient (with inclusion of the covariate age; Rittmo & McIntosh, 2021; Rittmo & McIntosh, 2023). We only compared the individual inspection behaviour in the low-cost condition, as we found that controls and patients significantly differed in this condition (Supplementary Materials). Table 3 displays the results of the single case statistics. We found that five of the patients with an abnormal memory score also showed

Table 3. Single case statistics for the mean number of inspections per correctly placed item in the low-cost condition for each individual in the patient group.

ID	*M* inspections per correct in the low-cost condition	Z-CCC [95% CI]	*p*-value	Proportion controls scoring higher (% [95% CI])	Abnormal memory capacity
3001	3.84	3.92 [2.66, 5.03]	<.001 ***	0.01 [0.00, 0.08]	Yes
3002	3.91	4.19 [3.04, 5.22]	<.001 ***	0.02 [0.00, 0.12]	Yes
3003	1.66	−0.51 [−0.84, −0.15]	.687	68.71 [55.74, 80.1]	
3006	2.2	0.78 [0.27, 1.25]	.230	22.97 [10.55, 39.21]	
3007	1.61	−0.45 [−0.99, 0.10]	.664	66.39 [46.03, 83.78]	
3008	2.18	0.63 [0.27, 0.96]	.273	27.32 [16.81, 39.42]	
3009	1.95	0.19 [−0.16, 0.53]	.429	42.85 [29.86, 56,45]	
3010	1.9	0.11 [−0.27, 0.47]	.459	45.87 [31.79, 60.65]	Yes
3011	1.4	−0.96 [−1.38, −0.52]	.820	81.97 [69.74, 91.65]	
3012	3.5	3.45 [2.55, 4.24]	<.001 ***	0.09 [0.00, 0.54]	Yes
3013	2.01	0.16 [−0.33, 0.63]	.441	44.12 [26.31, 62.85]	
3014	2.84	2.08 [1.46, 2.63]	.026 *	2.57 [0.42, 7.23]	Yes
3016	2.3	0.93 [0.50, 1.33]	.186	18.62 [9.25, 31.02]	
3018	3.46	3.35 [2.48, 4.11]	.001 ***	0.12 [0.00, 0.65]	Yes
3019	1.94	0.09 [−0.25, 0.43]	.466	46.64 [33.38, 59.86]	

Notes: We provide patients' mean scores, Bayesian Deficit Testing standardized effect sizes (Z-CCC) with 95% confidence intervals (CI) of task difference between the case and controls, *p*-values, and an estimation of the proportion of controls that would exhibit a more extreme conditioned score than the patient case. Tests account for age as confounding factor. Those who showed an abnormal score on neuropsychological capacity tasks are labelled.

*$p \leq 0.05$.

**$p \leq 0.005$.

***$p \leq 0.001$.

distinct eye-movement behaviour, while one patient with an abnormal memory score did not deviate from the norm group in terms of inspections per correct placement. Thus, whereas some individuals (in the control group) had a deficit in memory *capacity* (as measured by neuropsychological capacity tasks) but did not show deviant memory *use* (i.e., no excessive offloading in the copy task), other individuals (in the CVA population) showed both *capacity* problems and showed distinct memory *use* in the form of heavy reliance on offloading.

To summarize, the vast majority of people relies on the external world when information is readily available. When high-costs are imposed, some individuals switch to medium-loading, but seldom to high-loading, and many individuals are inclined to stick to low-loading. Individuals that show deficits in their maximum *load* can, but do not necessarily, show distinct memory *use* as indexed by inspection behaviour. This indicates that inspection behaviour has the potential to reveal individual signatures in memory usage that go beyond the mere measure of memory capacity.

Strategy shifting and performance stability: Switch costs

We analysed whether a larger change in inspection frequency from the low- to high-cost condition was related to a larger change in performance. In other words, we assessed switch costs. Log-transformed change scores are reported in Table 4. Note that we flipped log-transformed change values for LISAS performance to make the direction more intuitive: negative numbers now indicate a worse performance and positive numbers indicate better performance (see Methods). Values of 0 indicate stable behaviour.

The observed correlation across *all* participants was $r(49) = .35$ (95% CI:[0.08, 0.57], $p = .01$), indicating that a larger decrease in inspection frequency was associated with a larger decrease in performance. For controls separately, the correlation was not significant ($r(34) = .304$, 95% CI:[−0.03, 0.57], $p = .07$), while for the correlation was significant for patients separately ($r(13) = .55$, 95% CI:[0.05, 0.83], $p = .03$).

To test whether the correlation coefficients of controls and patients were significantly different and/or were driven by sample size differences, we conducted bootstrapping with 10.000 resamples using a resampling size of 15 out of 38 controls without replacement to match the group size of patients. The bootstrapped mean estimate was $r = .28$ (95% CI:[−0.20, 0.65]). The observed correlation for patients ($r = 0.55$) was not significantly larger than the bootstrapped estimate ($p_{\text{bootstrap}} = .226$, $z = 1.2$). We thus find no evidence for a difference in correlation estimates between groups.

In sum, the group as a whole showed that larger changes in inspection frequency were related to larger changes in performance, hence switch costs were present. We found no conclusive evidence for differences between groups. Figure 3 illustrates the relation between the *change in inspections per correct* and the *change in LISAS performance* for the group as a whole, and for the controls and the patients separately.

Table 4. Descriptives table for log-transformed change values of inspection frequency and LISAS performance.

		CVA patients			Controls		
Outcome		*N*	Mean (SD)	Range	*N*	Mean (SD)	Range
Inspection frequency	Log-transformed change value	15	−0.80 (0.25)	−1.22 −0.34	38	−0.77 (0.35)	−1.64–0.09
LISAS performance	Log-transformed change value	15	−0.27 (0.22)	−0.71–0.15	36	−0.31 (0.25)	−0.92–0.14

Notes: Negative numbers indicate a decrease in inspection frequency or a worsened performance. Zero indicates stable behaviour.

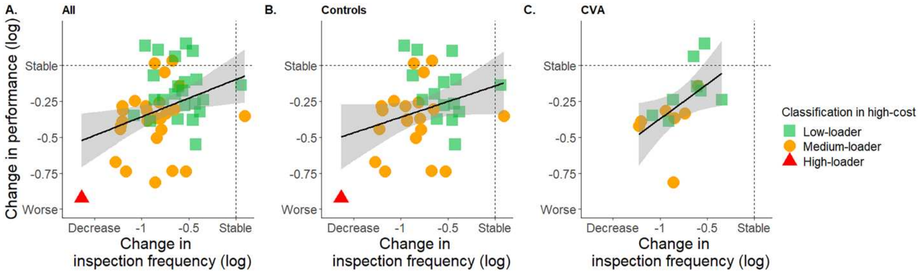

Figure 3. The relation between *the change in the number of inspections per correct* and *change in LISAS performance* for (A) all participants, and (B) the control and (C) the stroke (CVA) population separately. Dashed vertical and horizontal lines indicate a stable score. Negative values indicate a decrease, positive numbers indicate an increase. For performance, values above the dashed line indicate an improvement. Values below this line indicate a worsened performance. Squares indicate those who kept using a low-loading strategy in the high-cost condition, circles indicate those who used or started using medium-loading, and the triangle displays the one person that used high-loading.

Time post stroke. A linear regression in the patient group with factors age, time post-stroke, and condition as independent variables, showed that time post-stroke did explain differences in inspection frequency ($t = 0.8$, $p = .423$), performance ($t = 0.21$, $p = .83$), or switch costs ($t = 0.92$, $p = .373$).

Discussion

Working memory problems are common after stroke (Kimonides et al., 2018; Lugtmeijer et al., 2021). Memory rehabilitation aims to support defective working memory and to relief the internal memory load by advocating the use of external compensation strategies (i.e., *offloading*; Burnett & Richmond, 2023; Elliott & Parente, 2014; Gilbert, 2015; Gilbert et al., 2023; Morrison & Chein, 2011). While a growing body of literature shows that engaging working memory naturally co-occurs with exploiting the external world (Ballard et al., 1995; Böing et al., 2023, 2024, 2025; Draschkow et al., 2021; Droll & Hayhoe, 2008; Gray et al., 2006; Gray & Fu, 2004; Grinschgl et al., 2021; Hoogerbrugge et al., 2024; Kvitelashvili & Kessler, 2024; Melnik et al., 2018; Meyerhoff et al., 2021; Risko & Gilbert, 2016; Sahakian et al., 2023; Somai et al., 2020; Waldron et al., 2007), memory assessment generally does not allow for nor reflect the use of such external strategies but requires full memory capacity for successful task completion. Measures of capacity (e.g., how much one *can* remember) therefore lack specificity in testing how one *uses* their working memory when given the opportunity to use the external world as memory buffer. We have little objective insight into patients' spontaneous offloading behaviour when engaging working memory in interaction with the environment, while it is exactly this behaviour that is targeted with memory rehabilitation. With the overarching aim to objectively approximate individuals' working memory use after stroke, we tracked the eyes of inpatient and outpatient survivors of a cerebrovascular accident (stroke) in the subacute phase of recovery and healthy controls while they performed a reproduction puzzle task (i.e., Copy Task). In this paradigm, external information was either immediately available to inspect (low-cost) or after a delay (high-cost) to investigate whether and how individuals would adjust their preferred working memory load in response to this environmental change. Our aims were (1) to understand how patients recovering from stroke (in the subacute phase) spontaneously loaded their working memory or opted to rely on the external world, (2) to distinguish different and find predominant strategies at the individual level (i.e., low-loading, medium-loading and high-loading), (3) to interpret offloading behaviour from a clinical viewpoint, and (4) to explore whether and how strategy was adjusted when information was less readily available, and how this influenced performance for the individual (switch costs).

We observed distinct inspection behaviour for the stroke population: the majority of patients relied heavily on inspecting external information. It was common to inspect the example multiple times to place one item correctly (low-loading). Critically, a subset of patients showed excessive offloading when information was available at low costs: these patients showed up to four inspections with long encoding times to correctly place one item. Interestingly, this subset of patients comprised those who had decreased memory capacity as measured by traditional neuropsychological tasks. The current results are in line with previous findings showing that impaired memory is at the root of heightened offloading levels: patients with severe amnesia (Korsakoff's syndrome) used more inspections than controls (Böing et al., 2023), memory clinic patients and healthy controls with lower capacity relied more on the external world than those with higher memory capacity, and those failing memory capacity tasks according to clinical cut-offs were more inclined to use a high number of inspections (Böing et al., 2025).

Still, a consistent finding across these studies is that mere capacity cannot fully account for inspection behaviour. Theoretically, visual working memory capacity is about four items (although for more complex shapes such as our paradigm it might be fewer; Alvarez & Cavanagh, 2004; Cowan, 2001). Practically, the lowest verbal and visual working memory capacity spans observed in our current sample were three and four items, respectively. Yet, we barely observed anyone loading three or more items per iteration and thus using their full working memory potential.

There also was a number of individuals (one patient and multiple controls) that had abnormal memory capacity scores but did *not* show excessive inspection behaviour. Note that, indeed, several controls showed impaired memory capacity. One may argue that this is a flaw of the control group, but we argue the opposite: according to the normal distribution in the general population, 2.27% is expected to score very low and 13.59% to score low on neuropsychological tests, summing to 15.89% (based on cut-off rules for neuropsychological testing in the Netherlands). The distribution in our control group is in line with this pattern: 5.3% shows impairment and 13.2% scores below average, summing to 18.6%. Including controls with memory problems provides a realistic representation of the general population, while excluding them would imply selective filtering, which could bias the results and artificially inflate differences between patients and controls.

So, while all stroke patients who show excessive offloading also showed reduced memory capacity, memory capacity deficits did not automatically result in excessive offloading behaviour. This could potentially be explained by the extent to which the individual can recruit other cognitive functions that support working memory function in dynamic situations, such as decision making, monitoring/updating, and planning. We speculate that some stroke patients – but also individuals in previous studies (Böing et al., 2023, 2025) – exhibit (subtle) deficiencies in executive functioning that influence the way in which they have dealt with the complex and interactive Copy Task. Deficits in executive functioning may result in disinhibition, impulsive behaviour and a decreased ability to (self-)monitor, plan and pay attention (Suchy, 2009). On a task similar to ours – but administered in healthy controls – Kumle and colleagues (2025) assessed the relative contribution of attentional control and working memory capacity on the tendency to use higher memory loads (i.e., equivalent to the medium-/high-loading strategy in our task). Although the authors report an influence of both factors (higher scores related to a higher degree of memorization), they could not disentangle the unique contributions of either working memory capacity and attentional control to inspection behaviour as these constructs were highly correlated (Kumle et al., 2025; also see Unsworth & Spillers, 2010). Another explanation may be found in the ability to monitor and structure task progress. For example, those who systematically copy items from left to right and top to bottom show more efficient task completion, suggesting that this approach can serve as a monitoring and planning strategy that supports memory functioning and performance on the Copy Task (Sahakian et al., 2025). If patients have difficulties in monitoring/updating and planning, we would expect a disorganized, non-systematic approach, yielding a higher number of eye-movements towards the example puzzle to (re)locate remaining items, and, consecutively, worse performance. Because of time and work load constraints of our patients, we could not include tests on executive functioning, and we strongly encourage the inclusion of (a variety of) executive and speed measures in future studies.

It has been suggested that effort minimization is at the root of offloading behaviour (Burnett & Richmond, 2023; Gilbert, 2015; Meyerhoff et al., 2021; Risko & Dunn, 2015; Van der Stigchel, 2020). Although we did not specifically test this, one may argue that those who experience memory deficits have to put in relatively more effort (e.g., longer encoding, more conscious processing of information) to arrive at the same memory performance as compared to individuals that do not experience such difficulties. This would explain the high degree of spontaneous reliance on the external world for those who show abnormal capacity scores (also in Böing et al., 2023, 2025), even if inspecting information was hampered by adding a delay. Although we cannot state that individuals who are recovering from stroke do really *need* these frequent inspections per se, we do argue that frequent inspecting is the behaviour of choice when given the opportunity.

Interestingly, the *relative* tendency to either memorize or offload information appears to be stable across conditions. In other words, those who memorize most in the low-cost condition, are also those who memorize most in the high-cost condition (Kumle et al., 2025). However, the *absolute* tendency to either memorize or offload changes across conditions: inspection frequency decreases as high-cost conditions evoke memorization. This strategy shift does not only occur in healthy controls, but also in individuals with reduced memory capacity (Böing et al., 2023, 2024, 2025; Kumle et al., 2025; Somai et al., 2020) and is again observed in the current sample. Interestingly, the subset of stroke patients with abnormal memory capacity did decrease their inspection frequency, but still relied heavily on external information, executing up to two inspections for a single placement. As memory rehabilitation after stroke emphasizes using external strategies, we questioned whether sticking to the use of external strategies – even when accessing information in the external world comes at a higher cost – would show an advantage over using a relatively more memory-based strategy. Our results indicate that those who stuck to their baseline inspection frequency maintained a more stable performance than those who more drastically decreased the number of inspections.

Changing one’s strategy to a more memory-based strategy thus comes at a switch cost of performance, which would support the use of external strategies in memory rehabilitation. In contrast, such switch costs were not found in healthy adolescents performing a similar web-based copy task (Böing et al., 2024). The claim that external strategies are beneficial to performance is also contrasted by Kumle et al. (2025) who posit that the individuals with high-medium- or high-loading tendencies showed better performance than those with low-loading tendencies. Note, however, that performance was assessed only in terms of speed, and for conditions separately. An important remark here is that those showing a high-loading tendency could also be those who perform better in general, and that the effect on performance is not necessarily driven by the tendency to memorize, but rather by better global cognitive functioning. Baseline performance differences are not accounted for in such analyses. As it is likely that baseline individual differences (e.g., in psychomotor speed) were present in (some of) the stroke patients in our study, we refrained from analysing the relation between strategy and performance for conditions separately, and used within-subject analyses instead.

The (contrasts in) findings between groups suggests that older adults – and stroke patients specifically – may be particularly subject to switch costs, while healthy adolescents can adaptively switch their inspection behaviour without a cost to performance. Nonetheless, differences may also be attributed to the assumed homogeneity and characteristics of the population tested in the web-based study (adults under versus over 40, without versus with neurological conditions), and task-specific differences with regards to inspecting external information (using a cursor on a webpage versus using a body movement of 90̊ versus making an eye-movement to access external information). We know that making saccades towards external information comes at a cost (Koevoet et al., 2025), but other physical processes do as well (Mehta, 2016; Morel et al., 2017; Xie & Zhang, 2023). Directing the cursor or making the body turn to uncover external information may thus require more resources than making just a saccade. This would make frequent inspecting in a cursor-based version or body-turn version less attractive due to heightened motor costs, and would lower the threshold for memorizing to be more cost-efficient thereby incentivizing memorization to a larger extent than in the current study.

Even in healthy individuals different motor actions come at different effort costs, but stroke often has additional motoric consequences (Hendricks et al., 2002; Langhorne et al., 2009), as was also observed in our patient population. Slowed motor responses (here, longer mouse movements) increase the delay over which information has to be retained in working memory. Longer delays necessitate longer encoding times (Sahakian et al., 2024), and may explain decay of information for which an additional inspection is then executed. In addition, hemiparesis of the executive hand leads to decreased motor skills (Hatem et al., 2016), meaning that – even though one may be able to dress, eat, and operate the mouse – the patient may have had to put in more effort (physically, but also mentally) to initiate and act out goal-directed mouse movements. Logically, motoric deficits can be present for the contralesional hand, but even the ipsilesional hand may show decreased motor functioning (Johnson & Westlake, 2021; Smith et al., 2023; Winstein & Pohl, 1995). The simultaneous use of mental resources for a motor task, specifically for precision grip movements, and for internal memory storage, may result in reduced working memory performance (Xie & Zhang, 2023), driving a greater tendency to rely on the external world.

Apart from influencing dexterity and upper extremity functioning (Mani et al., 2013), lesion side is also likely to have influenced the type of memory problems that are encountered. Individuals with damage to the right hemisphere are described to show impaired immediate visual memory while immediate verbal memory abilities are intact, whereas left-sided lesions more often result in impairments in verbal memory (Logie, 2011). Regarding copying behaviour and visuospatial memory, dissociations in functionality between both hemispheres can be very subtle: van Asselen et al. (2008, 2009) used a task that assessed categorical versus coordinate spatial object-location bindings. Only a small difference in task layout, such as adding grid cells to a screen instead of presenting an empty screen, already elicited differential processing between the hemispheres with a dominance for the left versus right hemisphere in processing categorical and coordinate spatial representations, respectively. However, as soon as spatial information had to be integrated with object information and recalled (as is needed in our copy task), this lateralization effect disappeared. Unfortunately, right sided lesions were underrepresented in our sample, and our sample was too small in general to draw conclusions on the effect of laterality of stroke on inspection behaviour and the type of memory subprocesses involved. Further research should elucidate potential lateralization effects. Further, the patients in the current study were in the early or late subacute phases of recovery. This population was recruited to reflect those to whom we generally begin offering memory rehabilitation. Their behaviour reflects spontaneous performance in subacute stroke patients, but findings cannot be directly generalized to patients in the chronic phase. Future studies should elucidate the effect of phase post stroke. Nevertheless, previous research in chronic conditions (e.g., in Korsakoff syndrome, Böing et al., 2023) has shown similar behaviour.

Irrespective of these considerations, using inspection behaviour as an index of offloading versus memorizing advances our knowledge of how memory impairment drives working memory deployment in dynamic visual tasks. The studies outlined above and their differences in outcomes emphasize the highly interactive and fluid nature of a trade-off between inspecting external information versus internalizing information in working memory. One could argue that our reproduction task does not generalize to daily behaviour because the task constraints differ from those that are promoted in rehabilitation practices (e.g., writing things down on a notepad, a whiteboard, or smartphone). However, notwithstanding their differences, the commonality between all these tasks is that patients can interact with and exploit the external world. When teaching patients to use external strategies, we train them to create an external memory buffer from which they gather the information they need at the moment they need it. The oculomotor system – and thus the method of eye-tracking – offers a unique perspective on the use of offloading during basically any (visual) memory task, as it is by virtue of the visual system that we internalize, thus memorize, external visual information from that buffer – regardless of whether that is in written form or as purely visual representation. Although we do not intent to generalize our findings to *any* other free-choice task, we argue that (re)inspection behaviour is of such a basic nature that it will be exerted in many free-choice tasks within a home or city environment.

Conclusion

Altogether, our study highlights that a vast majority of people – both patients and controls – avoided memory loading and heavily relied on the environment. Nevertheless, offloading versus memorization tendencies varied quite a bit between individuals, and a subset of patients showed excessive reliance on offloading. In line with earlier work (Böing et al., 2025), we found that reduced memory capacity related to, but did not automatically result in, offloading behaviour. Further, memorization increased when external information became less accessible, but this was not necessarily beneficial: there were switch costs of changing ones inspection frequency while adhering to an offloading strategy yielded more stable performance. This finding supports the promotion of external strategies in memory rehabilitation. We also pose that this type of free-choice paradigm is suited to serve as a starting point for quantifying spontaneous offloading behaviour, and for tracking changes in the use of external strategies over conditions and over time. Such an approach allows future studies to directly assess the effect of promoting external strategies in memory rehabilitation after stroke.

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Author contributions

Conceptualization: S.B., A.F.T.B., T.C.W.N., and S.V.d.S; data curation: S.B.; formal analysis: S.B.; funding acquisition: S.V.d.S.; investigation: S.B.; methodology: S.B., A.F.T.B., T.C.W.N., and S.V.d.S.; project administration: S.B.; resources: S.B., and A.F.T.B.; software: S.B., and A.F.T.B.; supervision: A.F.T.B., T.C.W.N., and S.V.d.S.; visualization: S.B.; writing – original draft: S.B.; writing – review and editing: S.B., A.F.T.B., T.C.W.N., and S.V.d.S. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Informed consent statement

Informed consent was obtained from all subjects involved in the study. Written informed consent was obtained from the patient(s) to use their data in this paper.

Institutional review board statement

The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the Faculty Ethics Review Board of the Faculty of Social and Behavioural Sciences at Utrecht University (protocol numbers protocol numbers 21-0485, 22-0069 and 22-0284). The local ethics committees of De Hoogstraat and De Parkgraaf also approved the study.

Data availability statement

The data presented in this study are openly available at Open Science Framework at https://osf.io/95zx7/.

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